Senior Thesis

An Analysis of Organic Matter in the Vinini Creek Formation of East-Central Nevada

by
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Abstract

A stratigraphic section within the Vinini Formation at Vinini Creek records a rarely preserved extinction event at the close of the Ordovician in a nearly continous manner. The rich organic sediment of this section can be correlated chemostratigraphically, lithostratigraphically, and biostratigraphically to relate tectonic earth system dynamics. Three distinct stages of regional system dynamics are found to surround the extinction event. The chemical analysis is interpreted using Rock-Eval Pyrolysis methods which furthermore indicate a potential petroleum source within the Vinini Formation.

Introduction

The late Ordovician mass extinction event terminated over 60% of marine genera in a manner not well represented in the rock record worldwide (Sepkoski 1995). This extinction event is unique, as it occurred gradually as a result of dramatic earth dynamics. The section of the Upper Vinini Formation at Vinini Creek offers rare, nearly continous stratigraphy through a poorly represented portion of the Upper Ordovician. This section allows stepwise analysis of the chemostratigraphy, biostratigraphy, and sequence stratigraphy leading up to and during the extinction event of the late Ordovician. The section at Vinini Creek contains organic sediments that serve as potential source rocks for petroleum. The analyses of this work concentrate on the total organic content (TOC) and Rock-Eval Pyrolysis of the sediments in relation to biostratigraphy and lithostratigraphy in an effort to better understand regional earth system dynamics.

Location & Geoligic Setting

A hillside trench was bulldozed in the Roberts Mountains of east-central Nevada at Vinini Creek (see lower right hash mark #1 on geologic map in Figure 1). The section is approximately 30 meters in thickness and represents the uppermost portion of the Vinini Formation, the contact between the Ordovician and Silurian, and the lowermost portion of the Silurian Elder Formation.

The majority of sediments in the Roberts Mountains area were deposited along the western margin of Paleozoic North America during the Middle Cambrian to Upper Devonian in a continental rise setting. The assemblage was then thrusted to the northeast for more than 130 kilometers during the Upper Devonian to Lower Mississippian Antler Orogeny (Poole & Claypool 1984). The strata of the footwall is Devonian and older, formed from continental slope to continental shelf deposits. Mesozoic thrusting and Cenozoic rifting compounded with alluvial and volcanic deposition deformed the area.

The Vinini Formation was named and first described by Merriam and Anderson in 1942 on the eastern slopes of Roberts Creek Mountain, 25 miles northwest of Eureka. Rocks of the Vinini Formation outcrop from McKlusky Pass on the west to to the Sulpher Springs Mountains to the east, a distance of 20 miles. The rocks outcrop for 30 miles nearly continuously from the mouth of Dry Creek to the region east of Yahoo Canyon (Merriam & Anderson 1942).

The Vinini Formation is approximately 2600 meters thick in this area and is composed of an upper and lower member (Finney, et al 1999). The lower member is slightly thicker and consists of dark-grey, brown weathering quartzites, gray arenaceous, crossbedded limestones, finely laminated brown-gray siltstones, and occasional black shales. Lava flows and tuffs occur near the top of the Lower Vinini Formation. Graptolites, chitinozoans, and conodonts are abundant. The upper member consists of mainly bedded cherts with interbedded black organic shales. Chert layers are generally from 1 to 4 inches thick while shales are mostly under one inch in thickness. Along Vinini Creek, some black shales can be ignited (Poole & Claypool 1984). Approximately 25 gallons of oil per ton was yielded upon distillation of selected samples (Merriam & Anderson 1942). Graptolites are common throughout the upper member.

Biostratigraphy and Lithology of the Vinini Formation at Vinini Creek

The Vinini Formation at Vinini Creek was defined by abundant graptolite assemblages that occur throughout. Finney and others (1999) have subdivided the section. (Figure 2).

From 0.0 to 8.5 meters (intervals VAa through VAd), the lithology is tan-gray to gray-brown mudstones, containing graptolites. This assemblage of graptolites is considered coeval to the "Dicellograptus ornatus" graptolite zone (Figure 3).

From approximately 8.5 meters to 17.5 meters, the lithology is distinctly dark-brown to black organic mudstone of subunit VAe Figure 2). The graptolite assemblage reaches maximum diversity within this section and is coeval to the "Paraorthograptus pacificus" graptolite zone (Figure 3). Sixteen graptolite species are present (Finney, et al 1999). Above this organic-rich zone lies a 1.5 meter interval (~17.5-19m designated VAf) of brown siltstone and mudstone. The change from dark organic-rich mudstone to gray lime mudstone is gradational. The extinction of nine graptolite species (of 16) is evident at the base of interval VAf, although graptolite abundances remain high throughout.

Interval VAg (~19-19.5 m) contains one half meter of gray lime mudstone with three species of graptolites. At the base of VAg, graptolite abundance is noticeably reduced. The "Paraortograptus pacificus" graptolite assemblage has ended by the base of VAg, marking the end of a significant extinction event (Sepkoski 1995).

Structural deformation dislocates the Vinini Creek section at 19.5 meters and continues for several meters. This dislocation is subtitled "VB" by Finney, et al (1999). The continuity of stratigraphy is restored in subsection VCh. This inerval contains approximately four meters of interbedded tan-gray lime mudstone and laminated mudstones. Carbonate beds are more common in the VCh series, thickening upsection. The uppermost carbonate beds are highly deformed.

Graptolites occur commonly but not abundantly in the lower portion of the VCh. The "Normalograptus extraoardinarius" graptolite biostratigraphic zone ends within the VCh at ~22 meters. The uppermost portion of VCh (~22-24 meters) represent the "Normalograptus persculptus" graptolite biostratigraphic zone, in which graptolite genera noticeably radiate. The uppermost, highly deformed carbonate layers of the VCh represent the uppermost portion of the Vinini Formation and form a disconformable contact with the overlying Silurian (Llandovery) Elder Formation. This disconformity marks the boundary between the Ordivician and Silurian Systems.

The VCi is composed of green shales interbedded with black chert of the Silurian lower Elder Formation. Graptolites from the "M. convolutus" zone of the Llandovery Stage (basal Silurian) can be found within a thin bed 0.5 meters above the disconformity. A significant amount of time representing seven graptolite zones is missing at the disconformity. In uppermost Vinini Creek biostratigraphy, the extintion event for graptolites is clearly illustrated as a stepwise process that begins with the VAf interval. The underlying VAe interval represents the climax of graptolite radiation as marine conditions provided warm, nutrient-rich marginal settings. With Gondwanan glaciation, sea-level fluctuations allowed for cool current upwelling, which favored only certain species as the majority of graptolite species disappeared in subsection VAf. This extinction is also well represented in upper Ordovician stratigraphic sections in Siberia, Scotland, China, and the Canadian Arctic (Finney, et al, 1999). Interval VAg represents what would have been a sustained sea-level lowstand. Interval VCh indicates a setting that reflected a rise in sea level as glaciation waned. As a result, graptolite radiation renewed.

Biostratigraphic records of conodonts and chitinozoans are excellent in the section of the Upper Vinini Formation at Vinini Creek as well, but show a slightly different pattern (Figure 3). Contrasting with the recorded faunal turnover of most graptolite species upon the end of the "Paraorthograptus pacificus" zone, conodont and chitinizoan faunas remain regular until the disappearance of all Ordovician fauna within the "Normalograptus Persculptus" zone. This coincides with the disconformable Ordovician-Silurian contact and records maximum sea-level lowstand, directly linking extinction of conodonts and chitinozoans with the fall of sea level. Due to the sensitive shelf-margin habitat of graptolites, graptolite fauna record the extinction event in an earlier and more stepwise manner than the conodonts and chitinozoans owing to current upwelling (Finney, et al 1999).

The Carbon Cycle

Carbon deposition reflects ocean environment in terms of carbon isotopes. The nonradioactive carbon isotopes in sea water are carbon-12 and carbon-13. Being much more abundant, carbon-12 has a relative isotope abundance of 98.99% in modern seawater campared to 1.108% for carbon-13 (Odin 1982). The ratio of carbon-13 to carbon-12 in parts per mil is expessed as a deviation from standard Pedee belemnite (PDB). This ratio is recorded in the precipitation of carbonate from belemnites. The source of the carbonate lies in the transferral of carbon dioxide from the atmosphere to the ocean, from the decay of organic matter, or from photosynthesis. Since photosynthetic organisms prefer to incorporate lighter carbon-12, waters high in organic matter tend to have relatively low C-13/C-12 ratios. Such situations often occur when continental runoff enters the ocean after interaction with soils rich in organic matter. However, during the Upper Ordovician, evidence suggests a lack of soils. Deep, basinal waters also have a tendancy for low C-13/C-12 ratios from organic matter that sinks to the bottom in areas of long residence where precipitation is slowed. Changes in paleocurrents can lead to upwelling of these basinal waters, influencing coastal waters.

Tectonics therefore serve as an influence of the C-13/C-12 ratio. With uplift, increased erosion drives increased runoff into the ocean basins, decreasing levels of carbon-13. However, such episodes of increased erosion may oppose carbon-13 fractionating by burying sediments quickly enough to prevent the recycling of carbon-12-rich organics. Also, it has been suggested that the positive excursion of carbon-13 with increased sedimentation is driven by low levels of atmospheric CO2 and glaciation (Boggs 1995).

The Upper Ordovicain Carbon Excursion

Coinciding with the extinction event following the Upper Ordovician is a positive excursion of organic carbon-13 that also coincides with a sea-level lowstand brought on by glaciation and therefore, global cooling (Figure 3). This excursion follows an event of great organic burial recorded in the ~10 meter thick black mudstone at Vinini Creek. Without the existence of widespread land plants in the Ordovician, carbon isotope data suggest that the positive carbon-13 excursion is dependent on glaciation and increased removal of light carbon (carbon-12) by deposition of organic sediments due to tectonic mountain building events.

Organic Sediments and Rock Eval Pyrolysis

TOC

The Total Organic Carbon (TOC) of a sedimentary rock is defined as the weight percentage of organic carbon in the rock (Peters 1986). TOC content is related to grain size of the rock sample. Finer grained rocks such as shales and mudstones often contain higher TOC abundances than coarser grained rocks. TOC generally increases as energy and oxygen content decreases in depositional environments. Sandstones and skeletal limestones typically contain a negligible carbon content with TOC values commonly around 0.03% (Peters 1986). Black muds may have TOC values greater than 10%, whereas green shales typically contain less than 1% TOC. Using Rock-Eval Pyrolysis experiments, the minimum suggested value required to generate oil from a source rock is between 1.5% and 2%. Gas is possibly expelled from TOC as low as 0.4% (Peters 1986). Therefore, further analysis of the organic carbon in samples is restricted to samples with TOC of at least 0.4%.

Rock-Eval Pyrolysis Technique

The principal elemental constituents of sedimentary organic matter are carbon, hydrogen, and oxygen. The basis for Rock-Eval Pyrolysis lies in the quantification of these constituents in terms of percentages and ratios with respect to TOC and the amount of free hydrocarbons. There are four basic kerogen types in organic sediments based on hydrogen:carbon and oxygen:carbon ratios. Combined with TOC, Rock-Eval Pyrolysis is an effective and rapid technique used to differentiate these kerogen types in thermally immature and marginally mature organic matter.

S1, S2, S3, Tmax

Several initial measurements are made using Rock-Eval Pyrolysis as a function of heat and time called S1, S2, S3, and Tmax. A stream of helium used as an inert carrier agent is passed through 100 mg of a crushed rock sample that is heated initially to 300 degrees Celsius. The temperature is then increased by 25 degrees each minute until 550 degrees is reached. Analysis of the vapors is measured with a flame ionization detector (FID) and thermal conductivity detector (TCD). Three separate peaks form as a function of temperature. These peaks are S1, S2, and S3 (Figure 4). S1 occurs at or near 300 degrees Celsius and indicates the hydrocarbons generated by Rock-Eval Pyrolysis. The values are measured in milligrams of hydrocarbon per gram of rock. Between 350 and 550 degrees Celsius, hydrocarbons are cracked from the remaining organic matter, and are measured using a flame ionization detector in milligrams of hydrocarbon per gram of rock sample. These hydrocarbons are designated S2. From 300 to 390 degrees, carboxyl groups separate to form CO and CO2, and are measured with a thermal conductivity detector (TCD). These measurements determine milligrams of

CO_2 per gram of rock sample and are named S3. Additionally, the temperature at which maximum hydrocarbon generation (S2) takes place is designated Tmax. The generation of oil begins at approximately 435 degrees Celsius and ends at approximately 460 degrees Celsius (Peters 1986), representing the "oil window."

HI, OI, PI

Using the S1, S2, and S3 values in addition to TOC allows the calculation of HI, OI, and PI for determination of atomic ratios. The ratio of (S2/TOC) X 100, is the Hydrogen Index (HI), and generally ranges from 0 to more than 800 in rock samples. This correlates to the ratio of hydrogen to carbon atoms in a rock sample. The Hydrogen Index is of critical importance in terms of petroleum generation and is typically logged stratigraphically with TOC and S2 (Figure 5). The ratio of (S3/TOC) X 100, known as the Oxygen Index (OI), typically ranges from 0 to 200 in rock samples. Plotting HI versus OI is a method for recognizing kerogen type. Such plots, known as modified Van Krevelen diagrams, separate kerogen into four basic types; amorphinite (type I), exinite (type II), vitrinite (type III), and Inertinite (type IV) (see Figures 15,16, & 17). The different kerogen types commonly occur as a mixture. Production Index (PI), refers to the ratio of S1/(S1+S2), which evaluates the already generated hydrocarbon (S1) compared to the total generative potential (S1 + S2). Significant oil generation begins at PI = 0.1 and ends around PI = 0.4 (Peters 1986).

Vinini Creek Data

Samples were collected from a stratigraphic section of the Upper

Vinini Formation at Vinini Creek. The samples were carefully measured according to elevation. The samples were tested for organic content (TOC) and Rock-Eval Pyrolysis was carried out. Pyrolysis data for samples of less than 0.40% TOC has been omitted as inconclusive (Figure 6).

Results and Interpretation of Vinini Creek Rock-Eval and TOC Data

TOC, S1,S2, S3, HI, OI, and PI are plotted against the stratigraphic elevation of the Vinini Creek section (Figure 7), showing three distinct stratigraphic subdivisions. The first section consists of interbedded tan-gray lime mudstones and carbonates from the section base at 0 meters to approximately 9 meters. The TOC remains noticeably low in this interval (see Figure 8 for increased resolution of stratigraphic height vs. TOC), ranging from 0.13% to 3.04% and averaging 0.49%. Rock-Eval data is generally meaningless at TOC values of less than 0.4%.

The second distinct lithological and chemostratigraphical interval consists of significant organic-rich black shales from approximately 9 meters to 17 meters (Figures 7 & 8). Within this section the TOC rises markedly and remains rich throughout. The samples in this interval range from 0.69% to 37.1% TOC and average just above 5% TOC with three samples above 20% TOC. The S1, S2, and S3 values rise sharply in this section. Oxygen Index and Tmax remain relatively constant from the base of the Vinini Creek section. The Hydrogen Index values are relatively high, averaging above 400. This suggests the kerogen within these samples is of Type I or Type II, and is oil-prone , as high hydrogen to carbon ratios are the critical factor in source rock generatiom of oil (Peters 1986).

The third distinct, topmost interval at the Vinini Creek section has Rock-Eval Pyrolysis data that is similiar to the bottommost of the three intervals. Above 20 meters, the lithology is lighter tan-gray lime mudstones interbedded with carbonates. The TOC values decrease although they are less consistent than in the lowest (0-9m) section. Values range from 0.01% to 33.89% TOC and average approximately 2.5% TOC. Two samples are above 30% TOC, influencing the TOC average, and likely represent beds with transported sediment from the organic-rich underlying bed. Average values for the other Rock-Eval data above the 20 meter mark are low in relation, with a small number of hydrogen-rich samples of HI greater than 350 correlating with the samples high in TOC. However, above 21 meters the majority of samples with TOC greater than 0.5% have HI values below 250. Such levels indicate potential petroleum source rocks incapable of significant petroleum production.

Figure 9 plots sample elevation vs. TOC with samples separated into carbonates and non-carbonates. Carbonates are common in the lower 9 meters and have low TOC values. In the black shale section, less than 10% of the samples are carbonates, which contain less than 5% TOC, slightly less than the average of all samples within the section. In the section above the 20 meter mark, carbonates remain infrequent and contain TOC values less than 1%.

Figure 10 is a scatter plot of Tmax vs. stratigraphic elevation. The samples are divided into samples with TOC levels above or below 0.4%. Distribution was Gaussian, with values centered at approximately 432 degrees Celcius. The samples with lower TOC values show a wider distribution as Rock-Eval values are less consistent. Two samples stand out as slightly anomalous at Tmax levels of 425 degrees Celcius. Both samples occur near the top of the black shale section at 17.4 and 18.0 meters with TOC values of 5.56% and 3.29% respectively. Hydrogen Index values for these samples are only slightly lower than most of the nearby samples (358 and 392 respectively).

Figures 11, 12, and 13 all plot stratigraphic elevation vs. Tmax. Figure 11 plots all samples with TOC above 0.4% and displays a noticeable, but slight trend with Tmax increasing with depth. Again, the two samples at 425 degrees Celcius appear anomalous. Figure 12 plots Tmax vs. elevation, and includes samples with TOC values of less than 0.4% . These less rich organic samples only appear in the uppermost and lowermost stratigraphic intervals, and display a wide range of values. The trend in Tmax vs. height, however, is less pronounced. Figure 13 separates all samples with greater than 0.4% TOC into carbonates and non-carbonates. The carbonate samples with relatively high TOC values do not show any significant trend, although one of the anomalous samples at a Tmax of 425 degrees Celcius is a carbonate. Carbonate samples average 0.70% TOC. Noncarbonate samples average 2.7% TOC.

Figures 14 and 15 are plots of stratigraphic height vs. Hydrogen Index. The interval of organic-rich shales from 9 to 20 meters has higher HI values than the lowermost unit (0 to 9 meters) and uppermost unit (20 to 29 meters). Figure 14 separates the samples into organic-rich vs. organic-poor samples. Organic-poor samples are absent in the black shale and widely distributed in the units above and below with thin interbedded zones. These organic-rich samples have several anomalous values. One sample occurs at 6.7 meters and has a Hydrogen Index of 139. This sample is a carbonate with a TOC of 0.61%. This sample has a high Oxygen Index of 107. The organics of this sample are either of a different kerogen type than most of the other samples, or may represent oxidized sediments. A second sample at 0.0 meters has an Oxygen Index of 105 and a low Hydrogen Index of approximately 151. Two other samples of low Hydrogen Index lie in the upper portion of the section. One sample at 24.85 meters has an Oxygen Index of 146. The other sample at 22.84 meters has an oxygen index of 70, but is a carbonate sample. One sample with a low Hydrogen Index of 145 lies within the black shale at 18.5 meters from base. This sample also has a high Oxygen Index of 140, suggesting either a Type III kerogen source, prone to generating smaller amounts of gas and little oil, or oxidation of the sample has occurred following deposition.

Figure 16 plots S2 vs. TOC for all samples of greater than 0.4% TOC, and shows a clearly defined proportional linear trend. Slightly anomalous samples can be seen at TOC values of 10.26% and 33.89%. One of these samples at 21.15 meters has a very high oxygen index, but the other sample appears to trend with most other samples in terms of Rock-Eval. Both of these samples occur stratigraphically in the upper interbedded zone.

Figures 17, 18, and 19 are modified Van Krevelen plots of Hydrogen Index vs. Oxygen Index. Figure 17 separates the data into samples of less than or greater than 1.0% TOC. Samples of TOC greater than 1.0% have noticeably high hydrogen:carbon ratios and low oxygen:carbon ratios. These samples likely contain type I or type II kerogens. The organic-poor samples display a wider distributionof kerogen types, with low hydrogen content and high oxygen content. These samples are closer to type III kerogen. Figure 18 shows that non-carbonates are also closer to type I/II kerogen as opposed to the carbonate samples, which are widely distributed closer to type III kerogen. The carbonate samples are prone to oxidation from biological means following deposition. A depositional environment higher in energy and biologic activity than the environment in which muds are deposited can allow immediate oxidation prior to burial. Permeability in carbonates can allow oxidation to occur long after deposition has occurred. Figure 19 separates the upper interbedded zone of samples (section Vc), from the lower portion of the stratigraphic column. The samples from the black shale are clearly closer to type I/II kerogen with some dilution of type III/IV kerogen.

Conclusions

Geochemical Correlation

The nearly thirty meter section at Vinini Creek allows for an excellent analysis of a gradual extinction related to glaciation using lithostratigraphic, biostratigraphic, and geochemical methods. The zonation of graptolite and conodont species clearly marks the extinction event at approximately 19 meters, coinciding with shallowing from the onset of glaciation. The lithology also changes from black, organic-rich mudstones to brown and gray mudstones at this point. The loss of graptolite species is gradual, following the peak of species diversity and frequency within the period of time represented by the black mudstone from approximately 8.5 to 18 meters in which sea level achieved highstand.

The Rock-Eval Pyrolysis data are clearly correlated to the biostratigraphic and lithologic data. From 0 to ~8.5 meters (Zone I), TOC values are low for the gray-brown mudstones with correspondingly modest levels of graptolite species and frequency. The S1, S2, and S3 values for this portion of time are low as well. The HI values indicate marginally mature samples, but are not rich or oil-prone.

The ~10 meter section of organic mudstone (Zone II) is clearly represented in the Rock-Eval data. At ~8.5 meters the TOC levels become very high just as graptolite diversity and frequency noticeably increases. The S1, S2, S3, and HI values increase as well, with the HI rising to ~600. The black mudstones here are prone to producing oil and gas from kerogen sourced by algae and planktonic organisms. The TOC, S1, S2, S3, and HI levels drop during the marine lowstand at the extintion event, and continue into the Elder Fm. being much lower on average than levels in the black mudstone.

The Rock-Eval data plotted in HI:OI diagrams suggest that kerogen types in the Upper Vinini Formation represent a paleoenvironment that contributed to a positive carbon-13 excursion during the extinction event. The high HI and kerogen type suggest that sapropelic algae may have flourished at the onset of the deposition of the black mudstones, contributing initially to a negative carbon-13 excursion at the onset of the deposition of the black muds. However, depletion of carbon-13 soon reversed primarily in response to glaciation. Whether aided or not by depleted atmospheric CO2 to cause global cooling, tectonics drove glaciation and marine shallowing. With increased erosion aided by possible conditions favorable to decreasing the residency time of organics, vast amounts of organics were buried and preserved with little decay, removing lighter carbon from the marine dissolved carbon reservoir and trapping the lighter carbon-12 within the sediment. Therefore, immediately following the deposition of the black mudstones and the extinction event, a positive shift in carbon-13 is recorded in the rock record.

Source-Rock Potential

The potential of petroleum generation of the sediment from the Upper Vinini Formation is interpreted primarily by three criteria: quantity of organic matter (TOC), quality of organic matter (hydrogen content), and thermal maturity of the organic matter. The quantity of organic matter, measured in TOC, should be over 1.0% for commercial interest (Peters 1986). The mean TOC value for the measured section at Vinini Creek is 2.21% over nearly 30 meters. From 8.5 meters to 18.5 meters, the mean TOC is 6.18%. The quantity of organic carbon within the black mudstone section is favorable for a potential petroleum source rock.

The quality of the organic matter at Vinini Creek is favorable for petroleum generation as reflected in relatively high HI. The mean HI for the entire measured section is 374 (with calculations of samples with TOC<0.4% ommitted), an excellent value for commercial petroleum generation. For the organic-rich black shale, the mean HI is 446. The kerogen for these samples is high in sapropelic algaes of Type I/II as indicated by the plots of HI vs. OI. Such kerogen types are oil-prone in generation.

The Rock-Eval data of the sediments at Vinini Creek indicate a low to marginal thermal history. The mean Tmax values for all samples greater than 0.40% TOC at the Vinini Creek section is 433 degrees Celsius. The mean Tmax value for the black mudstone section is 433 degrees as well. The onset of the "oil-window" occurs at 435 degrees (Peters 1986). Low (<5%) hydrocarbon to total organic carbon ratios and low (<1%) saturate to aromatic ratios support the interpretation of the of an immature sediment (Pool & Claypool 1984). The thermal history of these sediments at Vinini Creek indicate that as an eastern, marginal portion of the Roberts Mountains allochthon, these sediments were never deeply buried.

The potential for the sediments of the Upper Vinini Formation at Vinini Creek should be considered for commercial petroleum generation. With adequate TOC levels and HI significantly above 300, thermally immature source rocks can be considered potential source rocks (Poole & Claypool 1984). The exposed rocks of the Vinini Formation extend for 30 miles by 20 miles. If, for example, 100 square miles of this known area of approximately 500 square miles is considered to contain the organic-rich mudstones of a ~ 10 meter thickness that yields 25 gallons of oil per ton of sediment (Merriam & Anderson), then up to roughly 4 billion barrels of oil could be ideally generated within the region. Certainly, only a small fraction this oil would be generated, migrated, and trapped. If only 1% has found a reservoir, that reservoir could contain 400 million barrels of oil.

With a complex geologic history including folding and thrusting as well as Basin and Range faulting, it is likely that a variety of traps may exist in the central Nevada area. Several valleys in central and eastern Nevada have not yet been thoroughly explored for resorvoir potential. The existing fields of commercial petroleum production within the region have been most often correlated to source rocks of the Mesozoic. The Vinini Fm. represents one of three strong possibilities for source rocks of the Paleozoic, though few existing petroleum fields correlate biologically with those sources. Further analysis of migration pathways, reservoir potentials, and crude-oil correlation need to be confirmed.

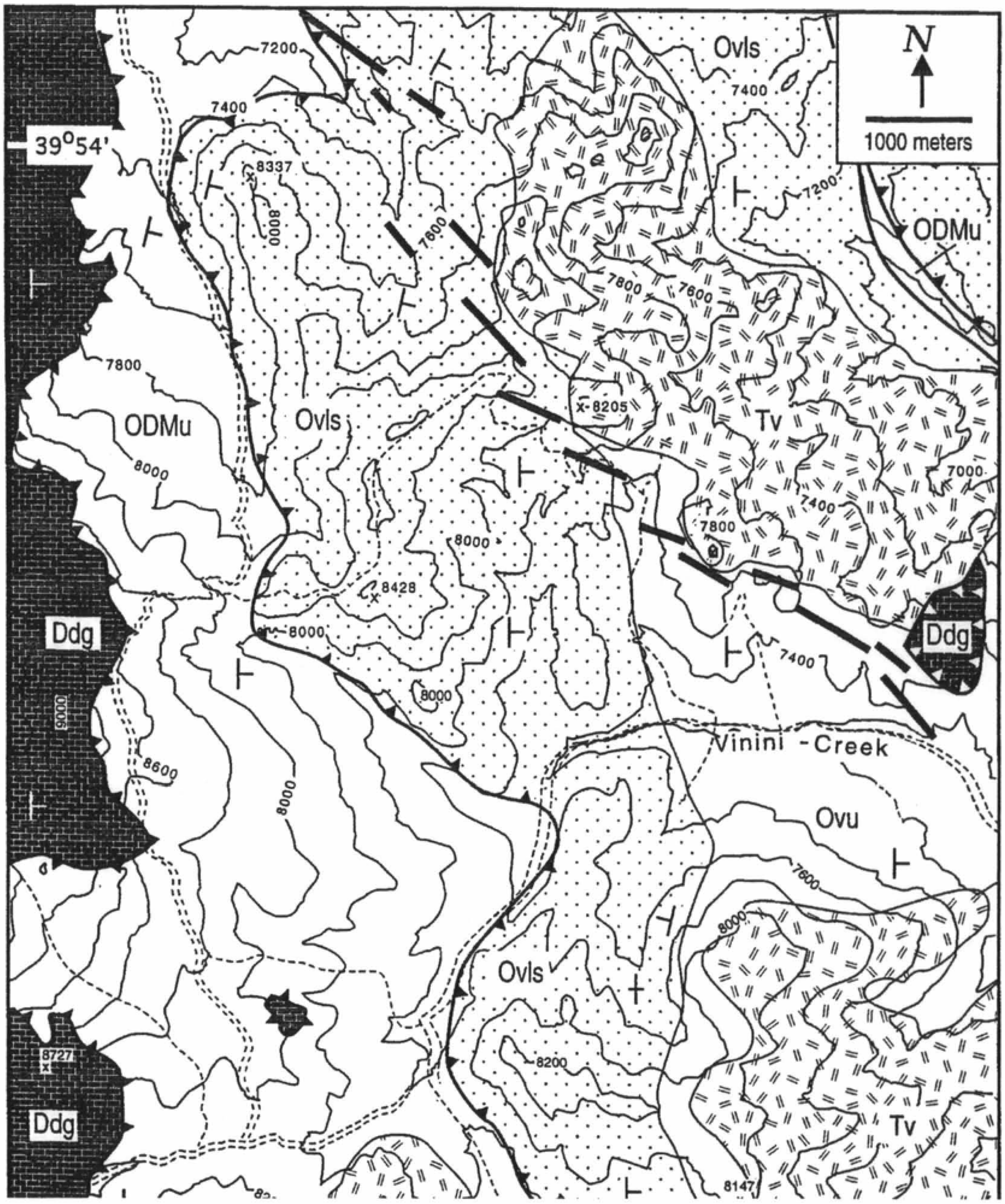

Figure 1. Geologic Map of Vinini Creek area showing the stratigraphic section at Vinini Creek along staggered hash lines. Ddg is Devonian Devil's Gate Limestone of lower plate of Roberts Mountains thrust; ODMu is undifferentiated thrust slices composed of the Mississippian Webb Fm., Devonian Woodruff Fm., and Middle Ordovician Vinini Fm.; Ovls is sandstone interval of upper half of lower member of Vinini Fm.; Ovu is upper member of Vinini Fm.; Tv is assorted Tertiary siliceous and mafic volcanic rock. Contour interval =200 ft. from Finney et al (1999).

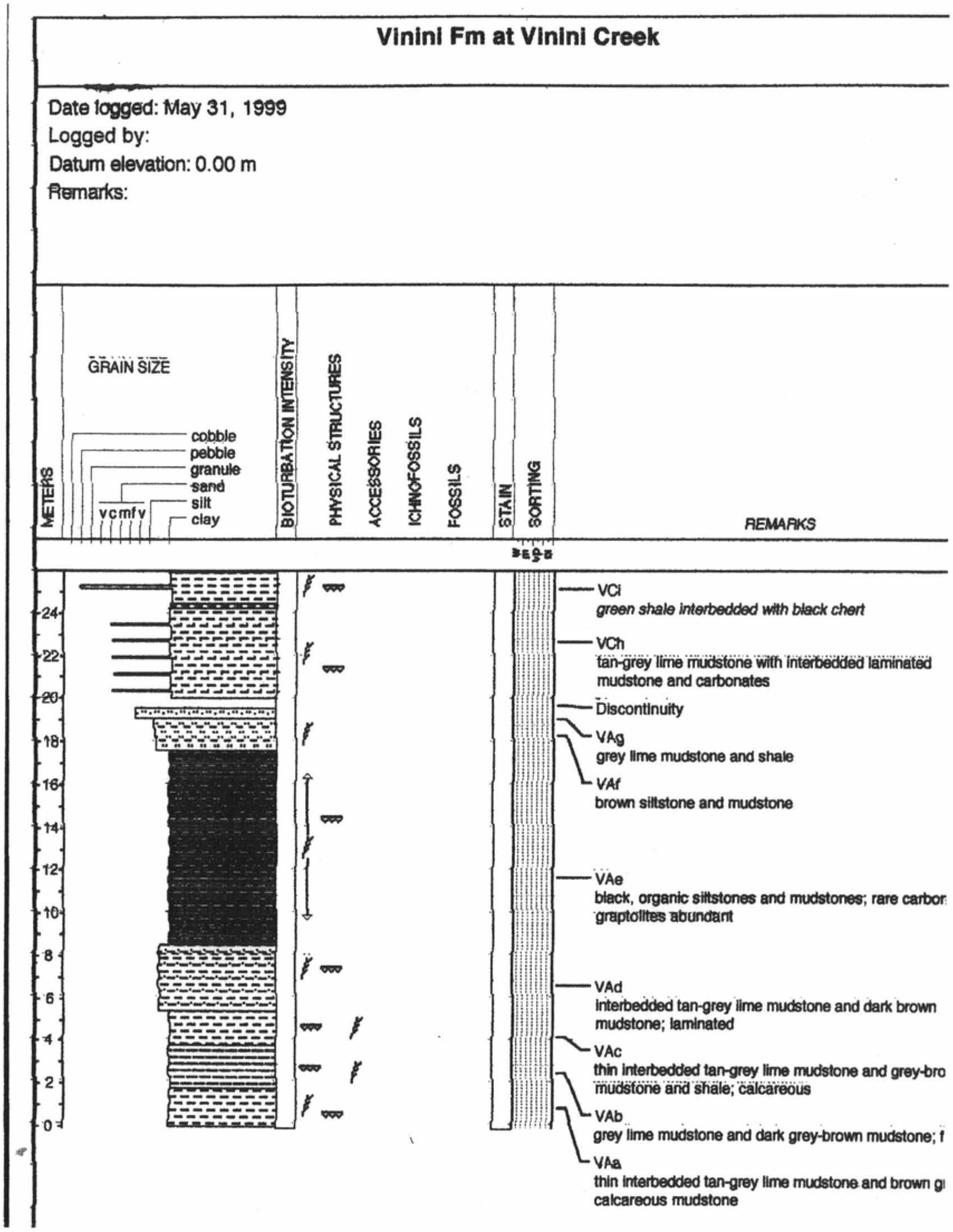

Figure 2. Stratigraphic Section of Upper Vinini Fm. at Vinini Creek showing subdivisions VAa-Vag and VCh-VCi as designated by Finney, et al (1999).

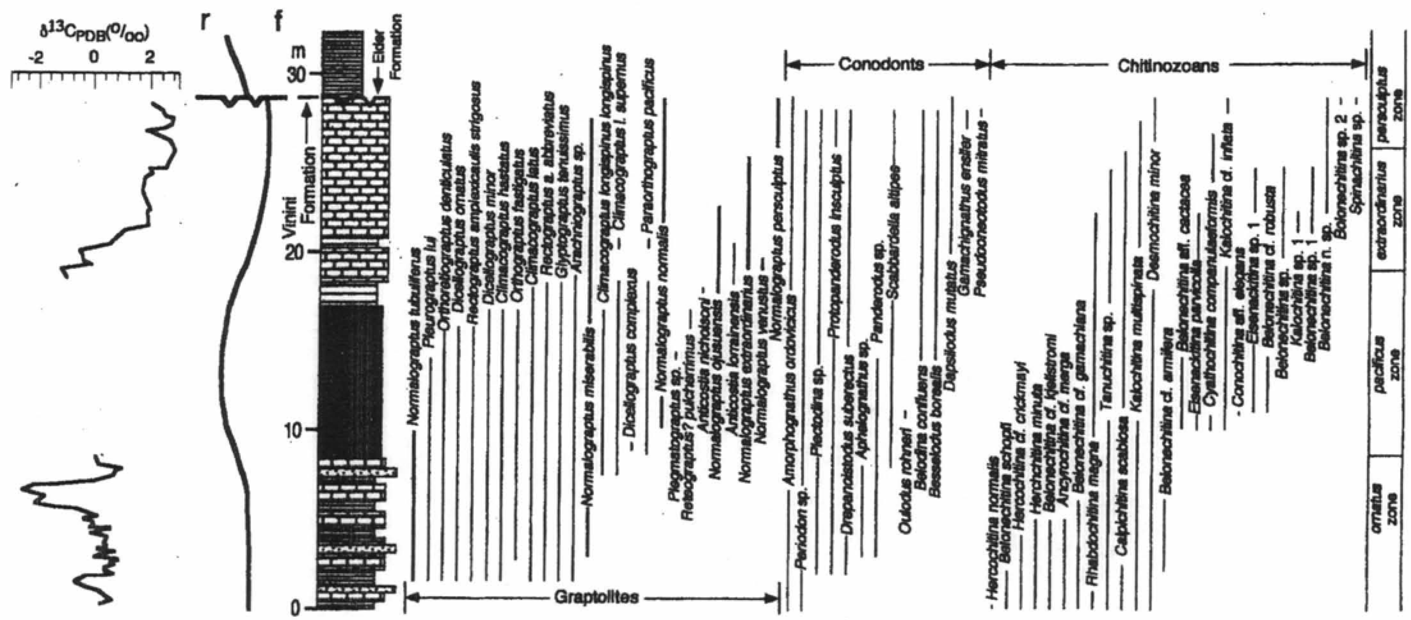

Figure 3. Upper 28.75 m of Vinini Fm. and lowest 4 m of Elder Fm.; ranges of graptolite, conodont, and chitinozoan species and graptolite zonation; carbon-13 profile; curve of rising (r) and falling (f) sea level. from Finney, et al (1999).

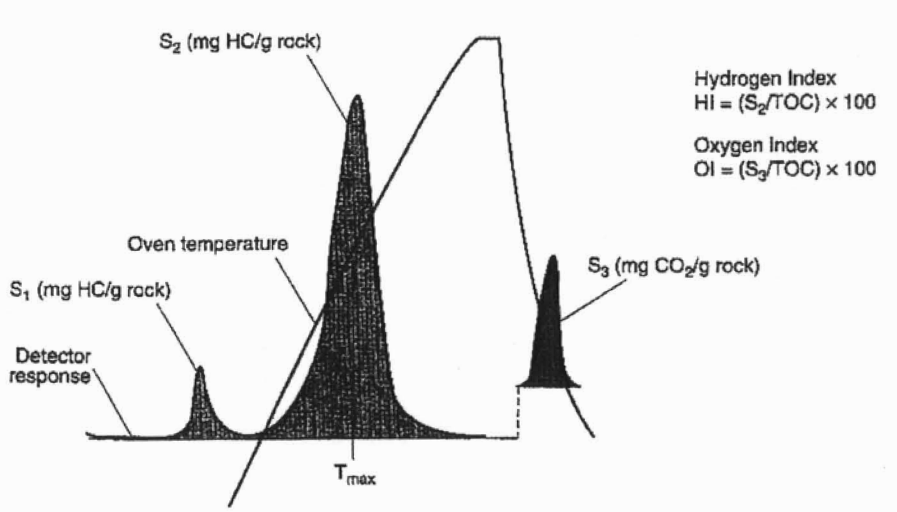

Figure 4. Pyrogram showing evolution of hydrocarbons and carbon dioxide from a rock sample with increasing temperature and time (left to right). (from Peters 1986).

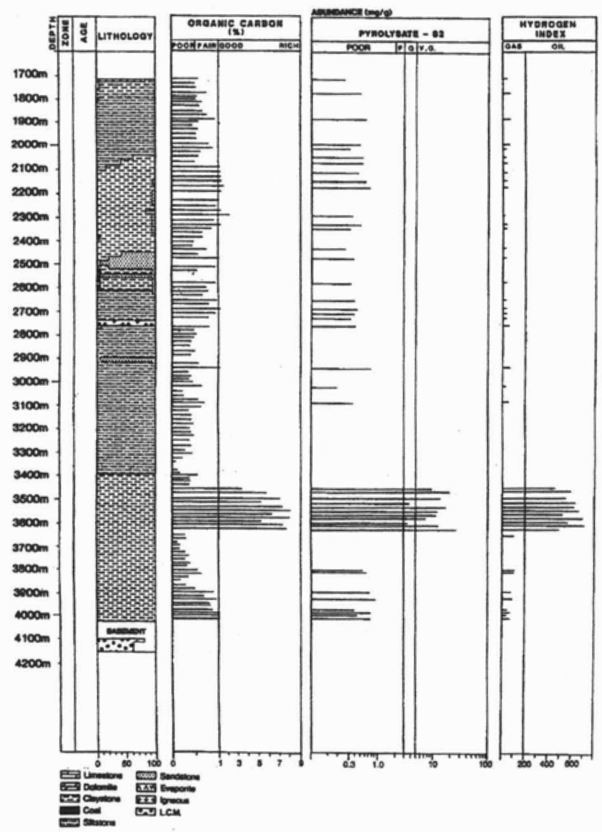

Figure 5. Example of geochemical well log showing lithology, quantity, quality, and maturity of source rocks in terms of TOC, S2, and HI. (from Selley 1998).

	DEPTH(X)	TOC(Y)	S1(Y)	S2(Y)	S3(Y)	TMAX(Y)	HI(Y)	OI(Y)	PI(Y)
1	0	0.43	0.06	0.65	0.45	439	151	105	0.08
2	0.07	0.21	--	--	--	--	--	--	--
3	0.1	0.13	--	--	--	--	--	--	--
4	0.3	0.21	--	--	--	--	--	--	--
5	0.4	0.69	0.1	1.06	0.43	438	154	62	0.09
6	0.5	0.27	--	--	--	--	--	--	--
7	0.78	0.28	--	--	--	--	--	--	--
8	1.1	1.64	0.18	4.36	0.86	438	266	52	0.04
9	1.1	0.32	--	--	--	--	--	--	--
10	1.25	0.22	--	--	--	--	--	--	--
11	1.5	0.38	--	--	--	--	--	--	--
12	1.6	1.09	0.13	2.74	0.76	435	251	70	0.05
13	1.85	1.06	0.25	2.56	0.68	436	242	64	0.09
14	1.9	0.26	--	--	--	--	--	--	--
15	2	0.24	--	--	--	--	--	--	--
16	2	0.2	--	--	--	--	--	--	--
17	2.15	0.6	0.25	2.21	0.32	436	368	53	0.1
18	2.2	0.62	0.23	2.02	0.27	437	326	44	0.1
19	2.3	0.66	0.26	2.38	0.32	435	361	48	0.1
20	2.45	0.4	0.12	1.3	0.26	434	325	65	0.08
21	2.5	0.33	--	--	--	--	--	--	--
22	2.6	0.39	--	--	--	--	--	--	--
23	2.65	0.29	--	--	--	--	--	--	--
24	2.7	0.34	--	--	--	--	--	--	--
25	2.75	0.54	0.22	1.94	0.25	435	359	46	0.1
26	2.84	0.35	--	--	--	--	--	--	--
27	2.9	0.52	0.15	1.67	0.39	435	321	75	0.08
28	3	1.39	0.35	4.18	0.93	434	301	67	0.08
29	3.28	0.32	--	--	--	--	--	--	--
30	3.33	0.31	--	--	--	--	--	--	--
31	3.4	0.63	0.1	1.34	0.49	439	213	78	0.07
32	3.41	0.31	--	--	--	--	--	--	--
33	3.45	0.26	--	--	--	--	--	--	--
34	3.5	0.27	--	--	--	--	--	--	--
35	3.57	0.4	0.11	1.19	0.3	434	298	75	0.08
36	3.6	0.27	--	--	--	--	--	--	--
37	3.65	0.4	0.1	1.41	0.32	436	353	80	0.07
38	3.74	0.31	--	--	--	--	--	--	--
39	3.76	0.2	--	--	--	--	--	--	--
40	4	1.9	0.27	6.25	1.15	435	329	61	0.04
41	4.07	0.27	--	--	--	--	--	--	--
42	4.16	0.57	0.17	1.72	0.35	435	302	61	0.09
43	4.23	0.29	--	--	--	--	--	--	--
44	4.3	0.25	--	--	--	--	--	--	--
45	4.4	0.28	--	--	--	--	--	--	--
46	4.48	0.31	--	--	--	--	--	--	--
47	4.56	0.29	--	--	--	--	--	--	--
48	4.6	0.2	--	--	--	--	--	--	--
49	4.65	--	--	--	--	--	--	--	--
50	4.88	0.39	0.1	1.39	0.29	434	356	74	0.07
51	4.9	0.36	--	--	--	--	--	--	--
52	5	1.34	0.12	3.79	1.12	437	283	84	0.03
53	5.05	0.2	--	--	--	--	--	--	--
54	5.1	0.23	--	--	--	--	--	--	--
55	5.2	0.22	--	--	--	--	--	--	--
56	5.25	0.22	--	--	--	--	--	--	--
57	5.29	0.21	--	--	--	--	--	--	--
58	5.66	0.3	--	--	--	--	--	--	--
59	5.74	0.26	--	--	--	--	--	--	--
60	5.94	0.22	--	--	--	--	--	--	--
61	6	0.27	--	--	--	--	--	--	--
62	6.04	0.18	--	--	--	--	--	--	--
63	6.42	0.17	--	--	--	--	--	--	--
64	6.7	0.61	0.04	0.85	0.65	439	139	107	0.04
65	7	0.16	--	--	--	--	--	--	--
66	7	0.2	--	--	--	--	--	--	--
67	7.04	0.61	0.28	2.93	0.16	435	480	26	0.09
68	7.3	0.27	--	--	--	--	--	--	--
69	7.6	0.59	0.25	2.57	0.21	434	436	36	0.09
70	7.85	0.2	--	--	--	--	--	--	--
71	8	0.28	--	--	--	--	--	--	--
72	8	2.07	0.26	9.31	1.17	432	450	57	0.03
73	8.26	0.28	--	--	--	--	--	--	--
74	8.5	3.04	0.27	10.87	0.98	432	358	32	0.02
75	8.75	1	0.12	4.04	0.55	432	404	55	0.03

Figure 6. Geochemical data from Upper Vinini Formation at Vinini Creek showing depth (m), TOC, and Rock-Eval data. (continued).

	DEPTH(X)	TOC(Y)	S1(Y)	S2(Y)	S3(Y)	TMAX(Y)	HI(Y)	OI(Y)	PI(Y)
76	9	23.6	2.15	103.23	6.66	432	437	28	0.02
77	9.59	9.09	1.22	42.67	2.36	431	469	26	0.03
78	9.76	2.46	0.31	12.68	0.39	438	515	16	0.02
79	9.85	1.18	0.28	5.63	0.34	435	477	29	0.05
80	10	1.03	0.1	4.02	0.4	430	390	39	0.02
81	10.1	15.95	1.71	70.19	3.41	432	440	21	0.02
82	10.22	1.02	0.14	4.21	0.41	432	413	40	0.03
83	10.3	5.52	0.55	26.97	1.46	429	489	26	0.02
84	10.5	0.96	0.27	5.05	0.34	432	526	35	0.05
85	10.7	19.99	1.53	82.1	5.15	434	411	26	0.02
86	10.85	10.16	0.98	51.07	2.77	432	503	27	0.02
87	10.87	1.38	0.14	7.27	0.24	437	527	17	0.02
88	12.4	1.28	0.29	5.96	0.39	437	466	30	0.05
89	13.06	1.29	0.15	5.63	0.48	434	436	37	0.03
90	13.11	3.6	0.29	21.47	0.64	437	596	18	0.01
91	13.25	6.47	0.56	34.28	0.96	432	530	15	0.02
92	13.26	1.87	0.08	7.3	0.69	433	390	37	0.01
93	13.43	3.16	0.42	16.06	0.61	436	508	19	0.03
94	13.61	1.78	0.19	7.55	0.61	434	424	34	0.02
95	14.05	1.84	0.25	8.08	0.98	431	439	53	0.03
96	14.76	5.21	0.39	25.09	1.57	430	482	30	0.02
97	14.9	37.1	4.07	171.5	8.73	433	462	24	0.02
98	16.84	5.89	0.47	28.58	1.39	434	485	24	0.02
99	17	4.39	0.48	19.79	1.27	433	451	29	0.02
100	17.4	5.56	0.34	19.91	2.02	425	358	36	0.02
101	17.5	5.19	0.48	24.88	1.39	436	479	27	0.02
102	18	3.29	0.27	12.9	1	425	392	30	0.02
103	18.5	0.97	0.05	1.41	1.36	432	145	140	0.03
104	19	2.59	0.42	11.33	0.65	432	437	25	0.04
105	19	3.05	0.52	13.86	0.37	428	454	12	0.04
106	19.11	0.72	0.21	2.57	0.25	435	357	35	0.08
107	19.2	1.39	0.12	4.86	0.6	435	350	43	0.02
108	19.26	0.69	0.29	2.92	0.32	435	429	47	0.09
109	19.28	1.2	0.27	4.88	0.46	434	407	38	0.05
110	19.31	2.8	0.71	14.04	0.83	432	501	30	0.05
111	19.5	1.94	0.5	12.07	0.56	432	622	29	0.04
112	20.05	2.12	0.39	10.34	0.7	433	488	33	0.04
113	20.1	0.34	--	--	--	--	--	--	--
114	20.5	0.42	0.05	1.14	0.69	433	271	164	0.04
115	20.83	0.23	--	--	--	--	--	--	--
116	21	0.23	--	--	--	--	--	--	--
117	21.05	0.4	0.4	1.54	0.34	433	385	85	0.21
118	21.15	33.89	2.19	112.21	15.54	434	331	331	0.02
119	21.46	0.87	0.15	2.8	0.56	431	322	64	0.05
120	21.5	0.74	0.46	3.13	0.52	427	423	70	0.13
121	21.83	0.34	--	--	--	--	--	--	--
122	22.15	0.21	--	--	--	--	--	--	--
123	22.23	0.45	0.2	1.83	0.26	430	407	58	0.1
124	22.3	0.62	0.08	1.72	0.54	436	277	87	0.04
125	22.6	0.41	0.32	1.83	0.28	431	446	68	0.15
126	22.75	0.26	--	--	--	--	--	--	--
127	22.84	0.53	0.07	0.76	0.37	437	143	70	0.08
128	23.1	0.26	--	--	--	--	--	--	--
129	23.25	0.57	0.05	1.58	0.52	435	277	91	0.03
130	23.55	0.33	--	--	--	--	--	--	--
131	23.6	0.79	0.04	1.83	1.1	437	232	232	0.02
132	23.6	1	0.73	5.01	0.36	431	501	36	0.13
133	23.83	0.29	--	--	--	--	--	--	--
134	23.98	1.6	0.27	5.85	0.84	431	366	53	0.04
135	24.1	10.26	0.7	21.6	6.88	432	211	67	0.03
136	24.25	0.04	--	--	--	--	--	--	--
137	24.45	0.22	--	--	--	--	--	--	--
138	24.7	0.12	--	--	--	--	--	--	--
139	24.85	1.86	0.16	2.71	3.15	429	146	146	0.06
140	24.925	0.01	--	--	--	--	--	--	--
141	25	0.86	0.14	2.02	0.89	429	235	103	0.06
142	25.25	0.21	--	--	--	--	--	--	--
143	25.45	32.19	2.39	132.92	10.44	431	413	32	0.02
144	25.5	1.34	0.1	2.87	0.75	433	214	56	0.03
145	25.9	0.22	--	--	--	--	--	--	--
146	25.9	0.11	--	--	--	--	--	--	--
147	26.625	2.48	0.33	8.71	0.94	432	351	38	0.04
148	27.25	0.48	0.09	1.06	0.52	430	221	108	0.08
149	27.5	0.12	--	--	--	--	--	--	--
150	28.5	0.19	--	--	--	--	--	--	--

Figure 6 (continued). Geochemical data from Upper Vinini Formation at Vinini Creek showing depth (m), TOC, and Rock-Eval data.

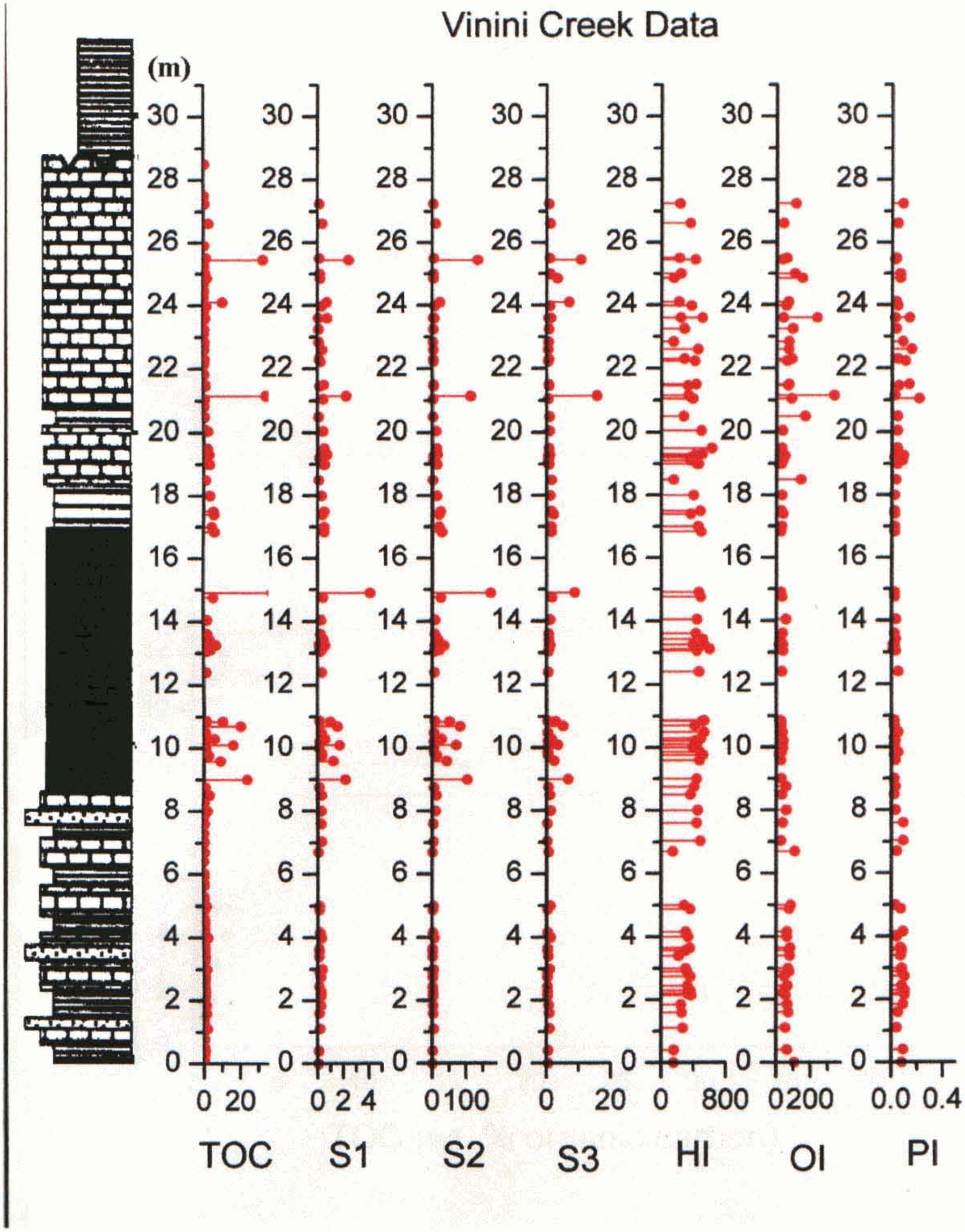

Figure 7. Stratigraphic height of section at Vinini Creek vs. TOC and Rock-Eval data.

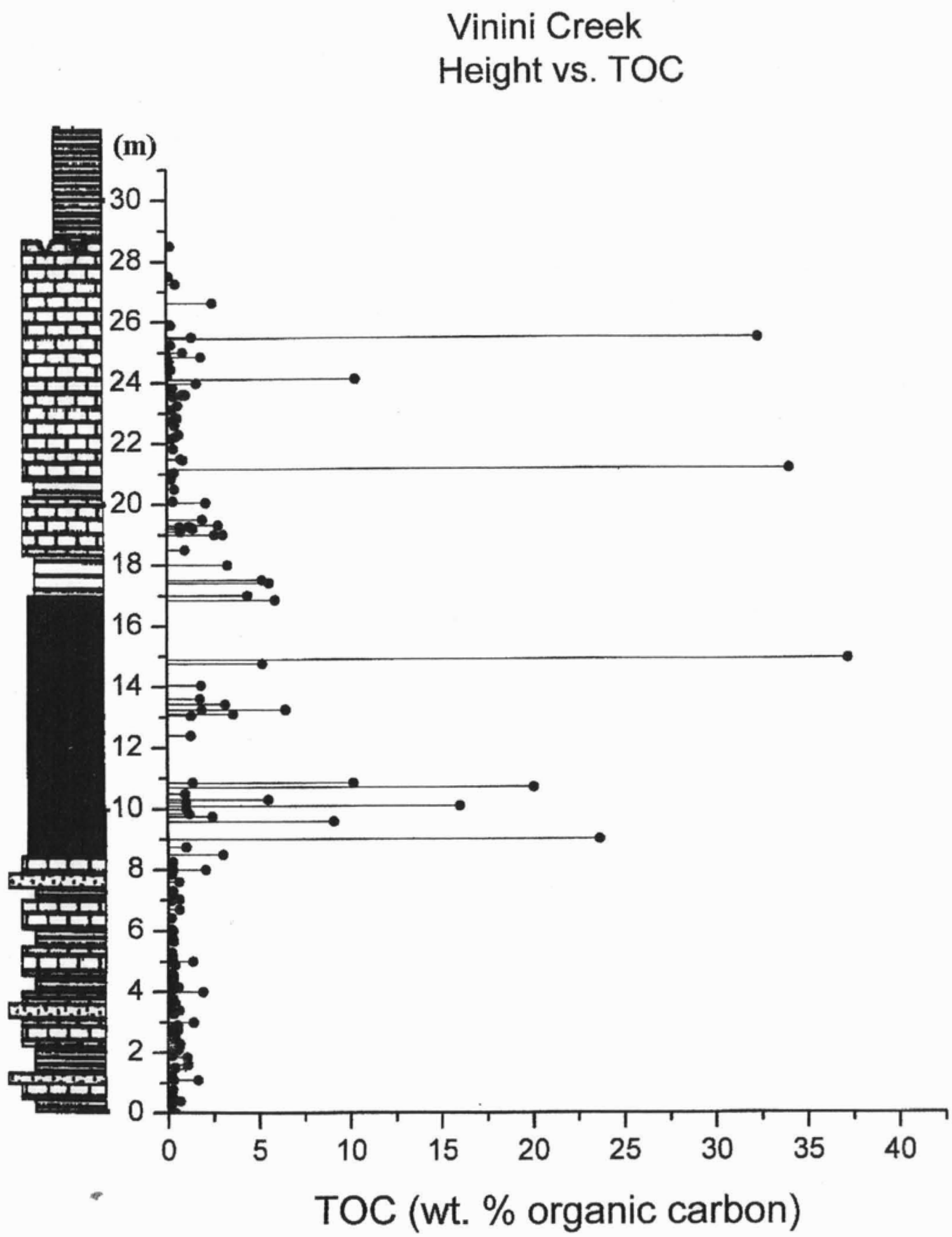

Figure 8. Stratigraphic height of section at Vinini Creek vs. TOC.

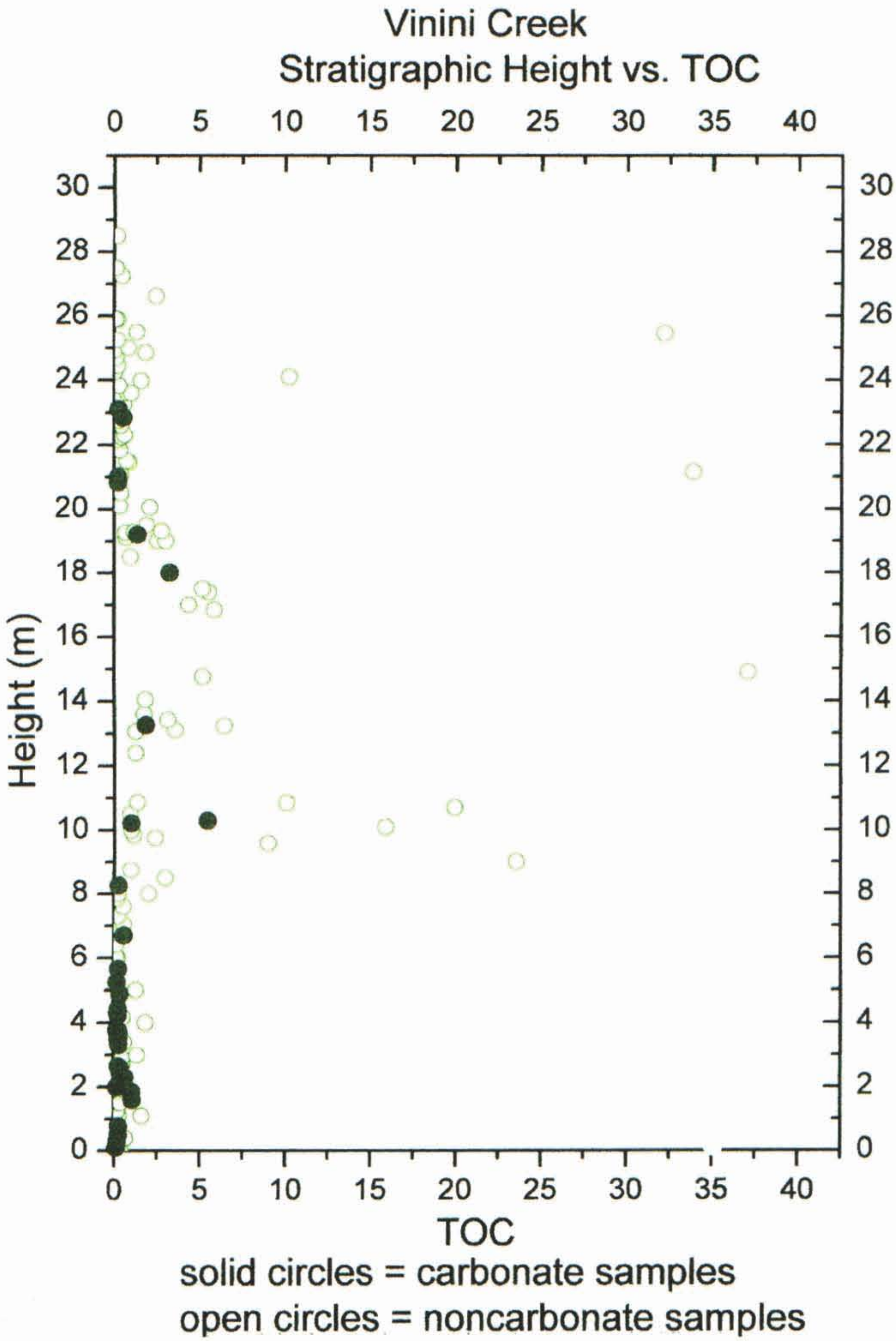

Figure 9. Plot of stratigraphic height vs. TOC from section at Vinini Creek with differentiation of samples from carbonates and noncarbonates.

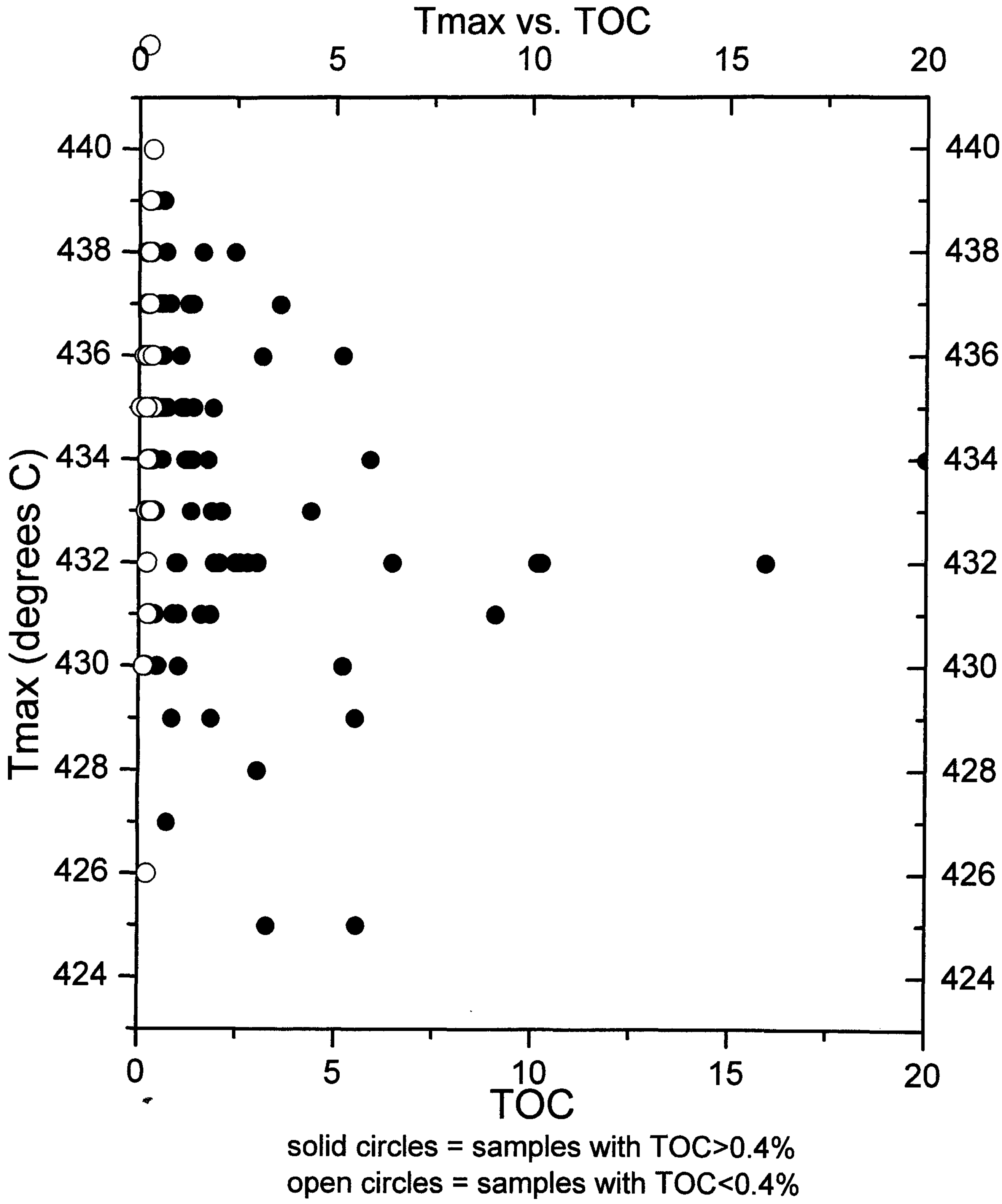

Figure 10. Plot of Tmax vs. TOC from section at Vinini Creek. Differentiating samples that are above or below 0.40% TOC shows samples that are higher in TOC cluster in a more accurate data set.

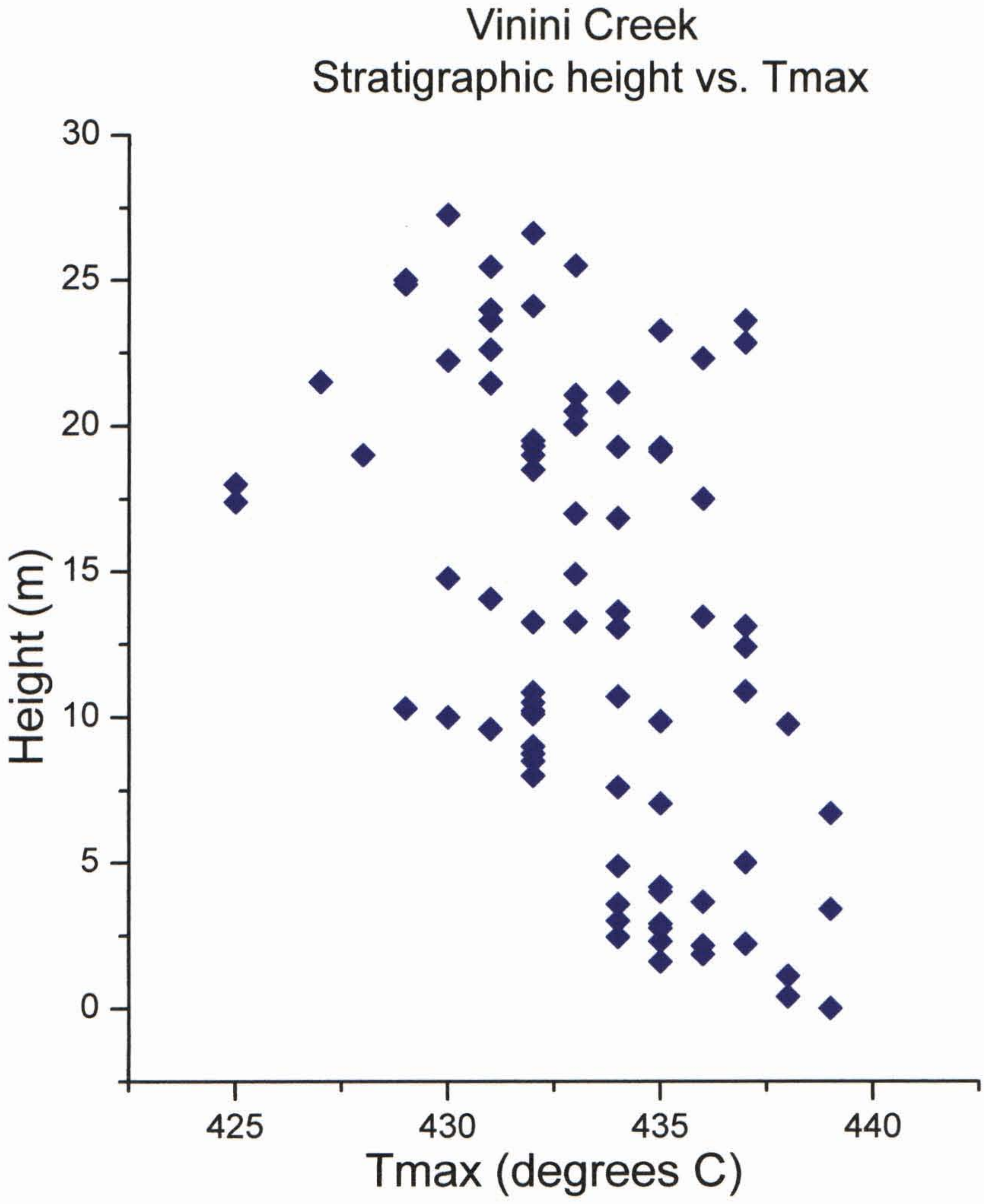

Figure 11. Plot of stratigraphic height vs. Tmax from section at Vinini Creek. Shows linear trend of inreasing Tmax with depth.

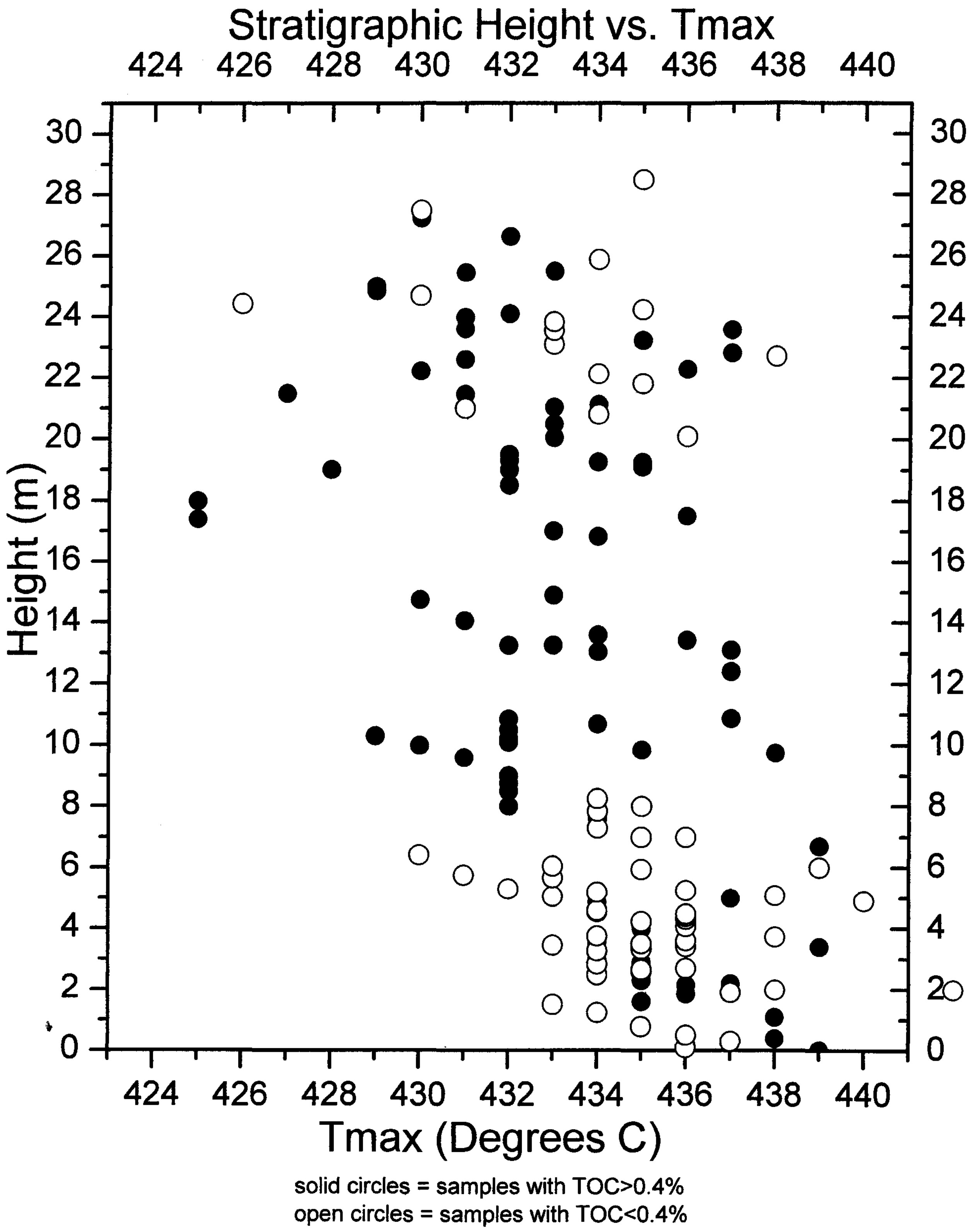

Figure 12. Plot of stratigraphic height vs. Tmax from section at Vinini Creek with differentiation of samples greater than 0.40% TOC and less than 0.40% TOC.

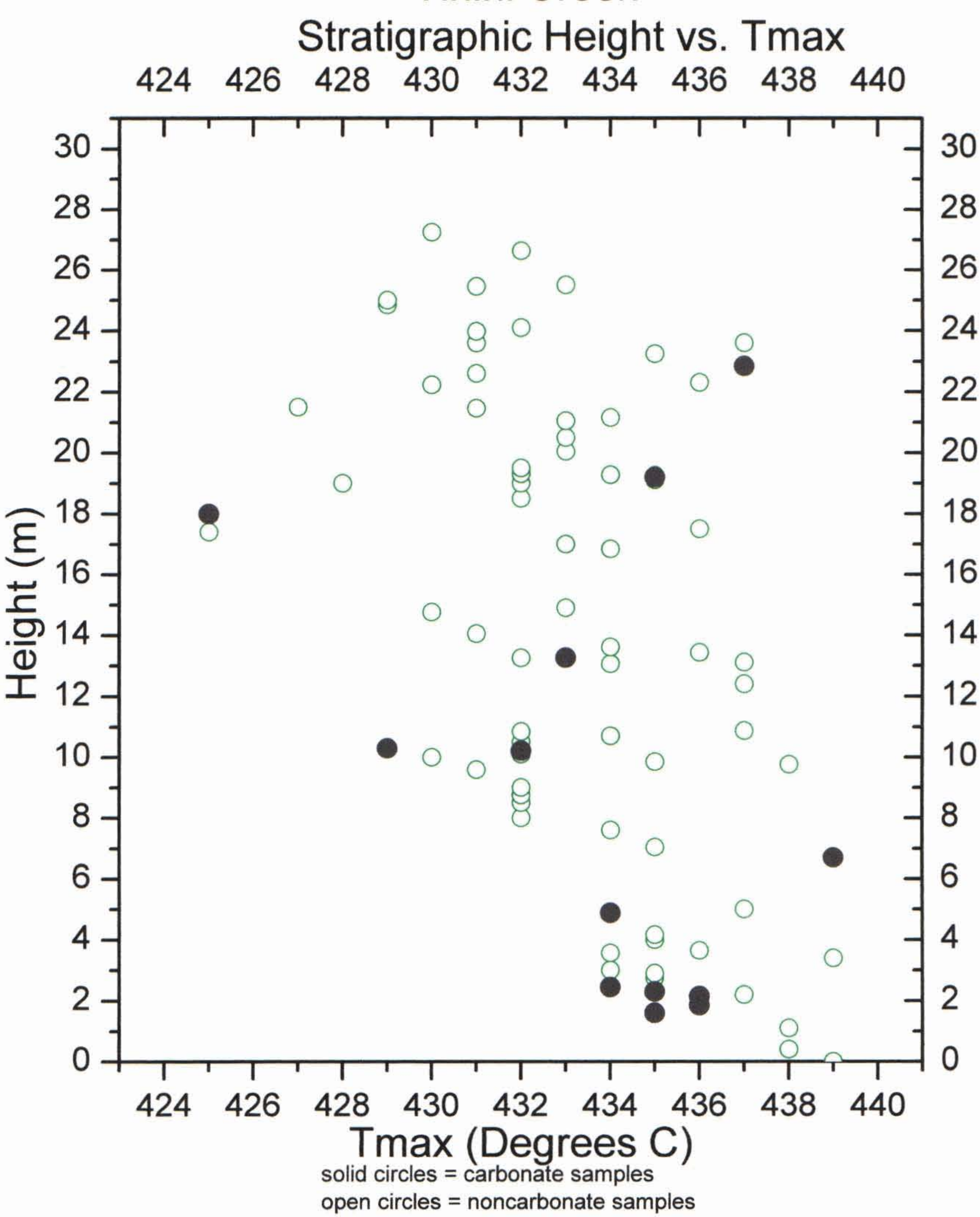

Figure 13. Plot of stratigraphic height vs. Tmax from section at Vinini Creek with differentiation of samples from carbonates and noncarbonates.

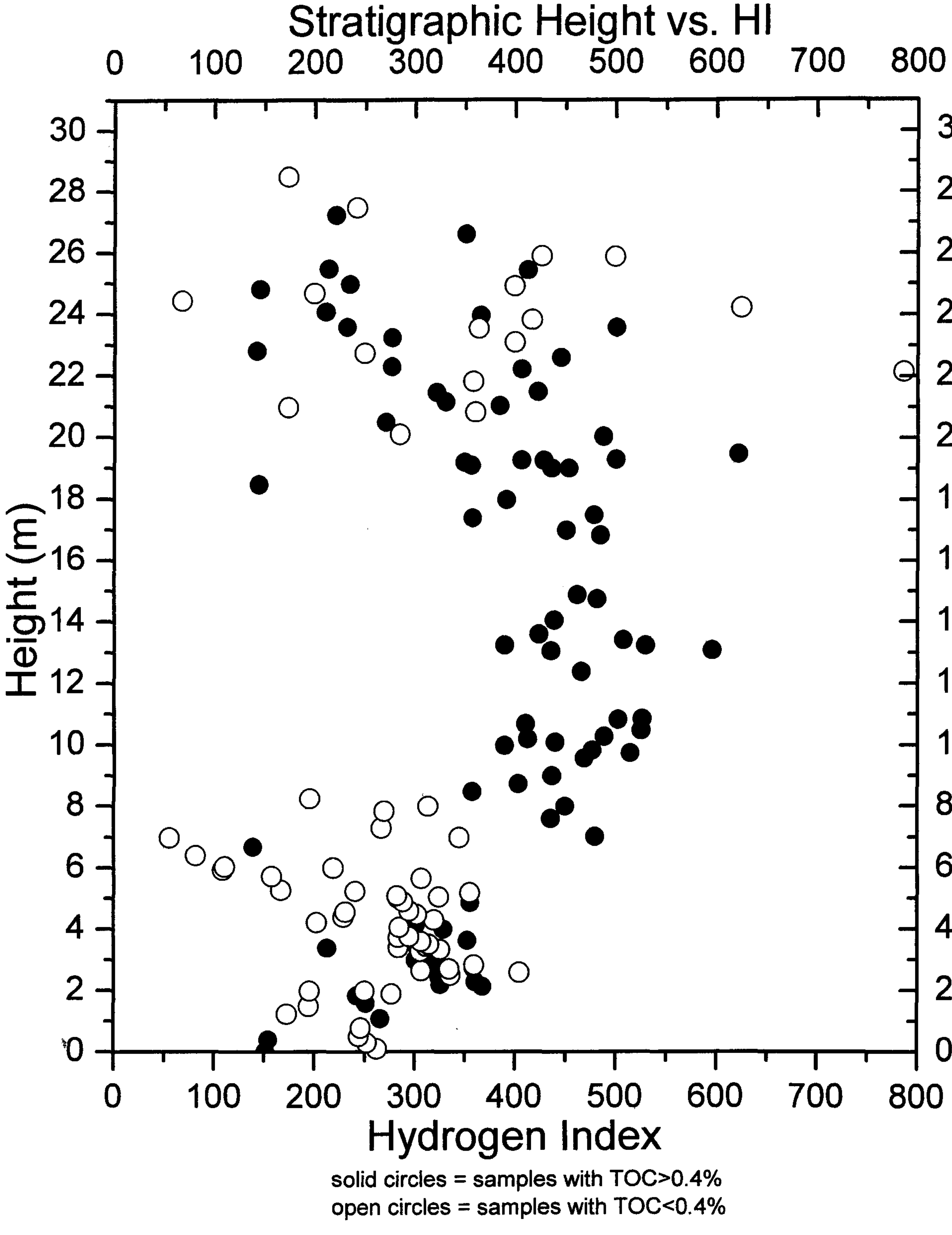

Figure 14. Plot of stratigraphic height vs. HI from section at Vinini Creek with differentiation of samples greater than 0.40% TOC and less than 0.40% TOC.

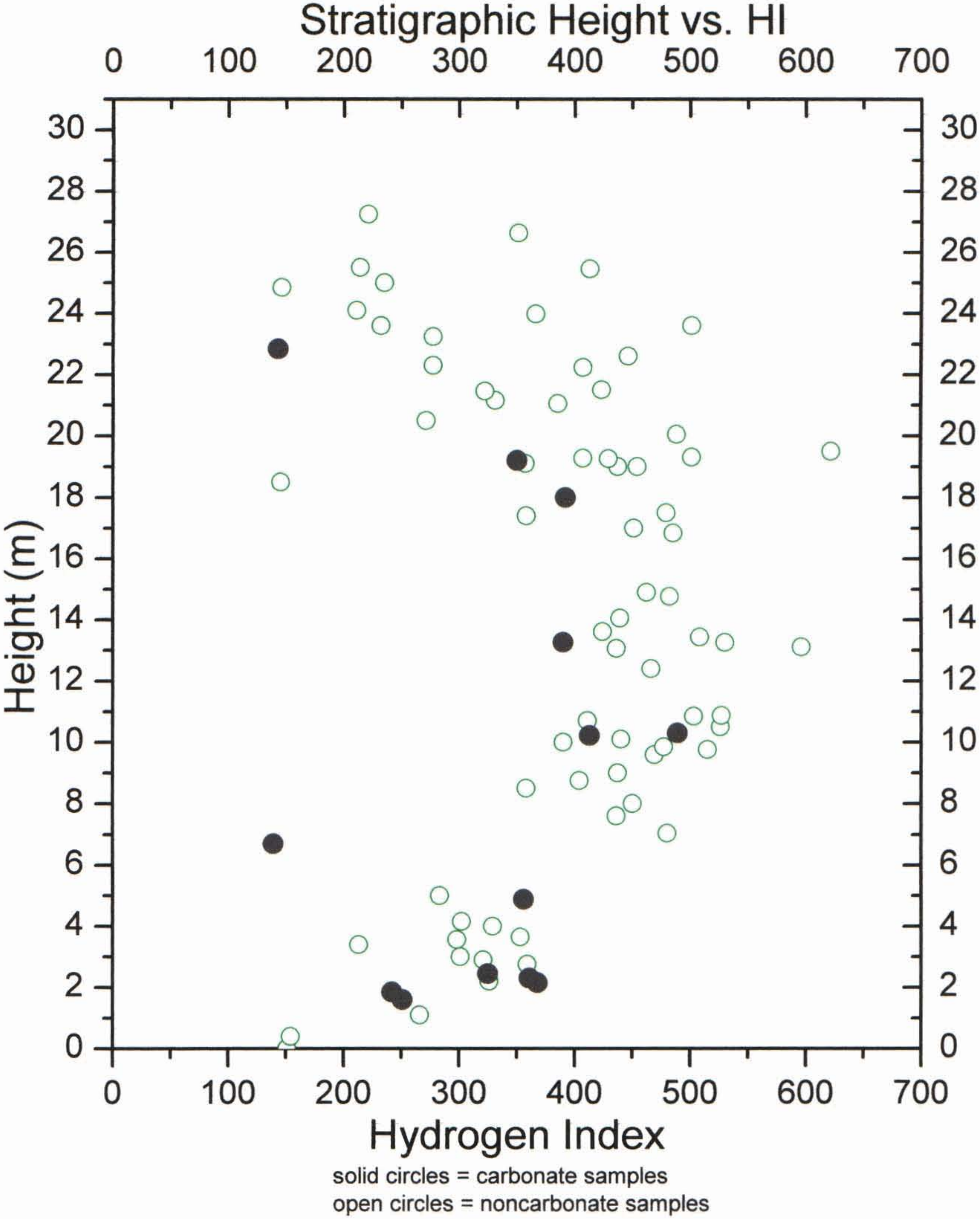

Figure 15. Plot of stratigraphic height vs. HI from section at Vinini Creek with differentiation of samples from carbonates and noncarbonates.

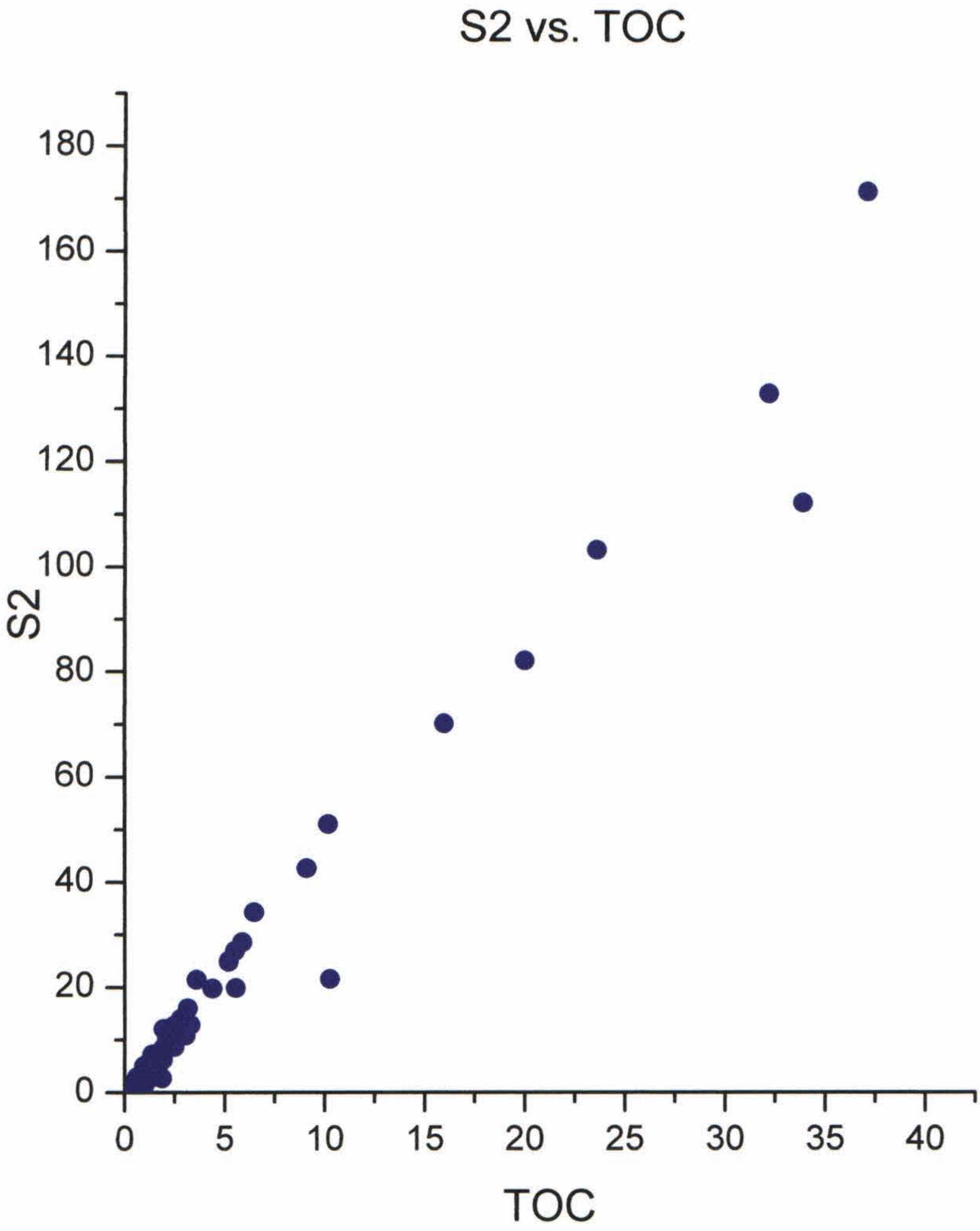

Figure 16. Plot of S2 vs. TOC from Vinini Creek Rock-Eval data showing linear trend of increasing S2 with increasing TOC.

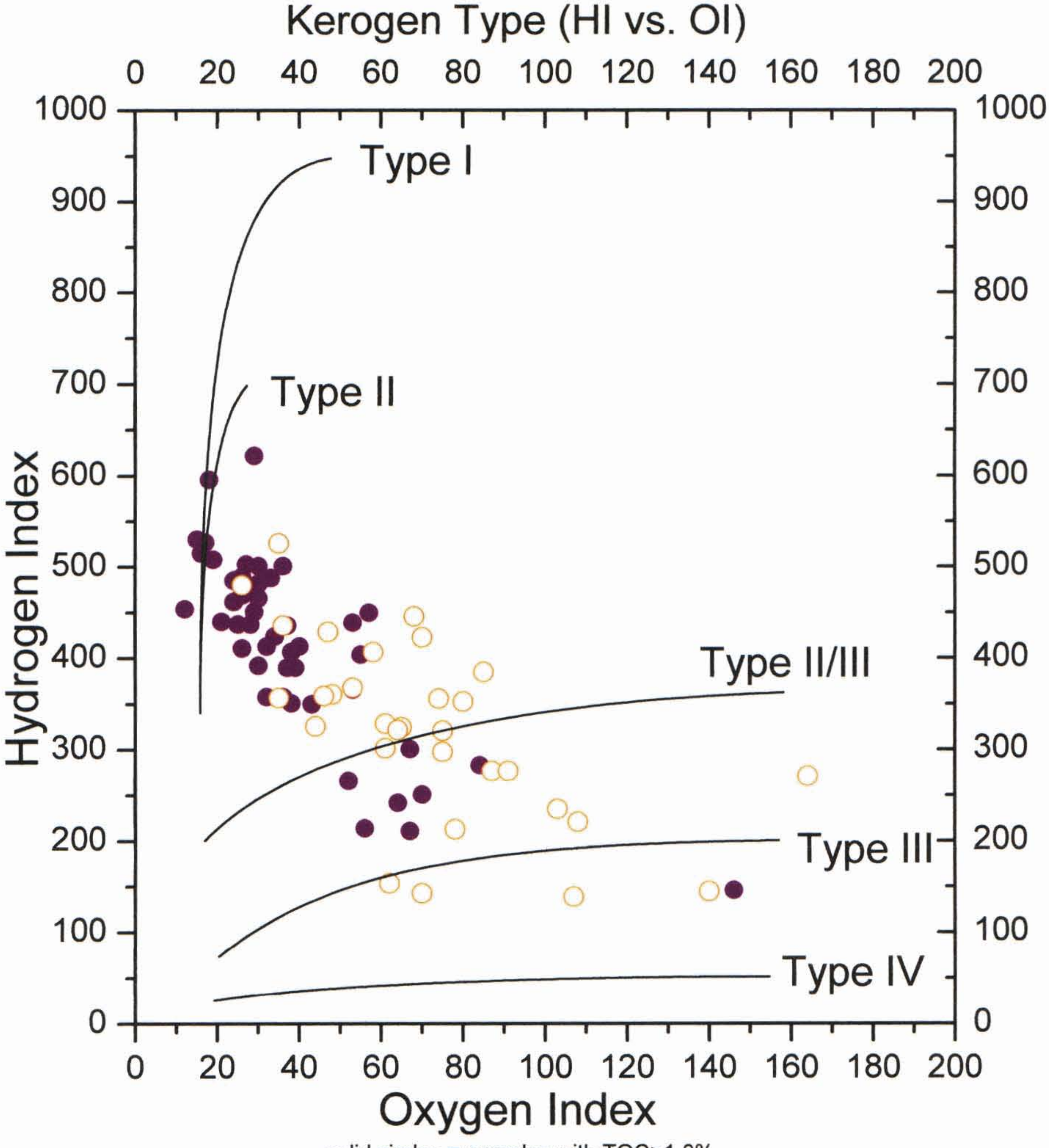

Figure 17. Plot of HI vs. OI (kerogen analysis or modified Van Krevelen diagram) with differentiation of samples greater than 1.0% TOC and samples less than 1.0% TOC.

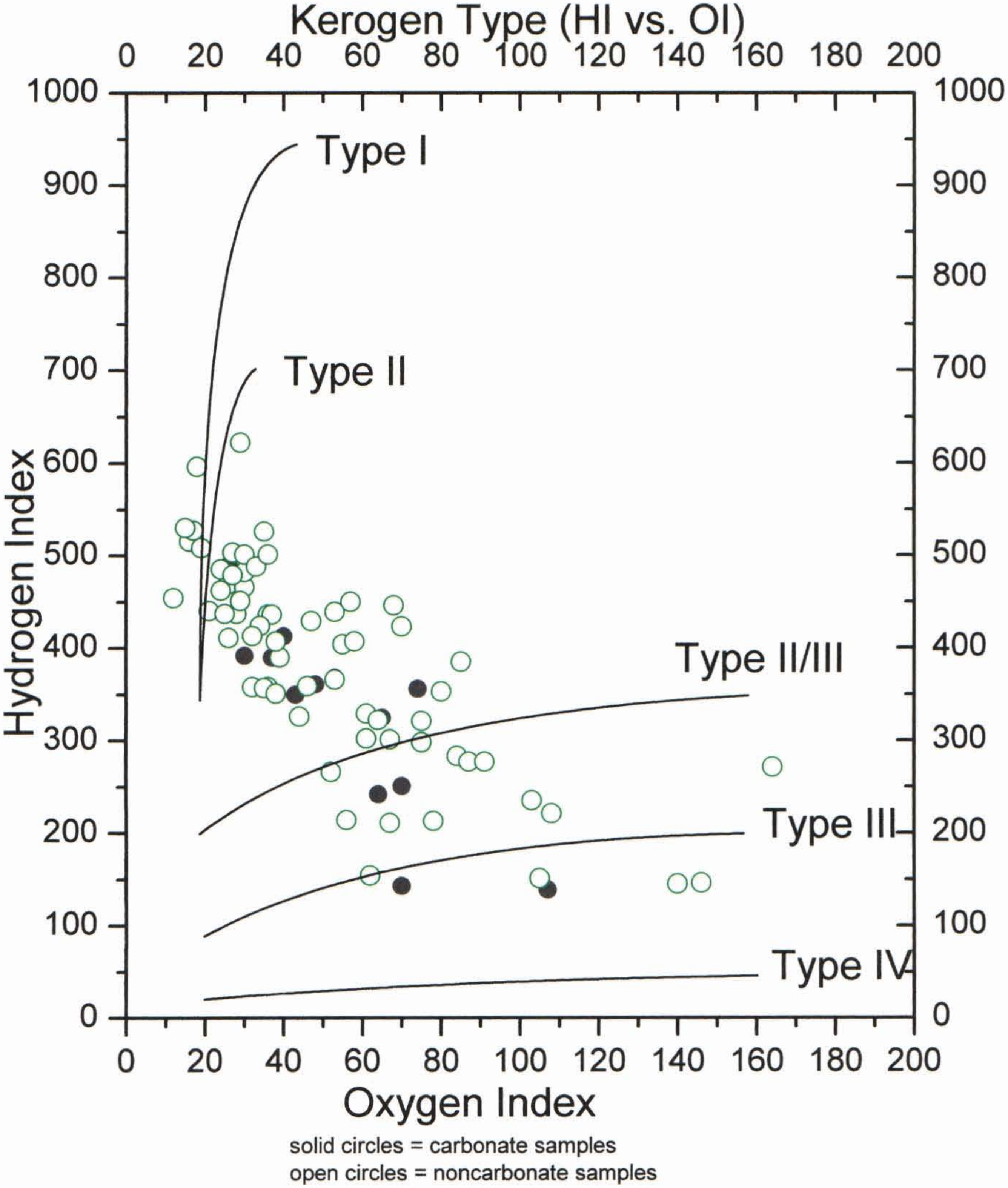

Figure 18. Plot of HI vs. OI (kerogen analysis or modified Van Krevelen diagram) with differentiation of samples from carbonates and noncarbonates.

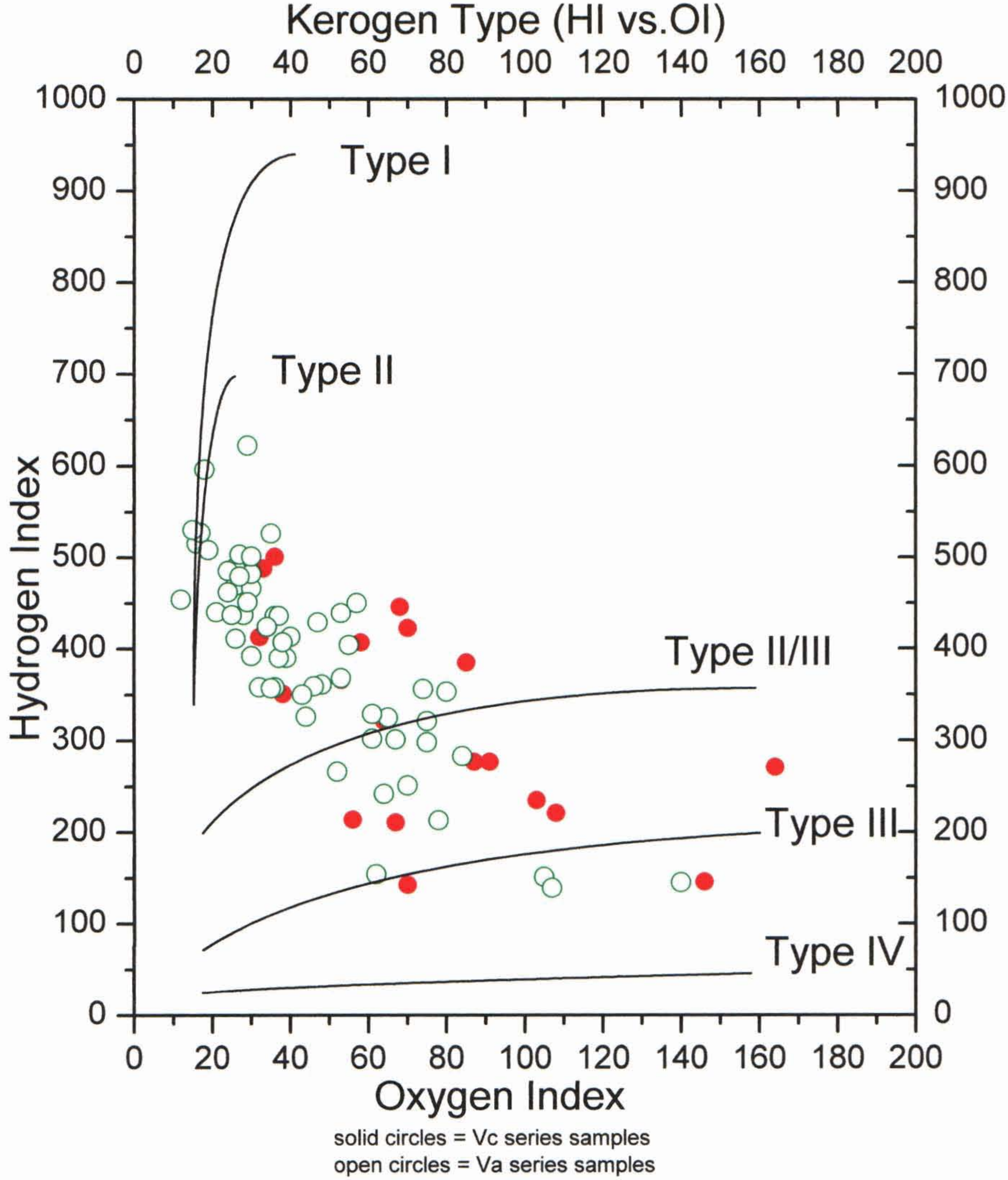

Figure 19. Plot of HI vs. OI (kerogen analysis or modified Van Krevelen diagram) with differentiation of samples from VA subunits and VC subunits.

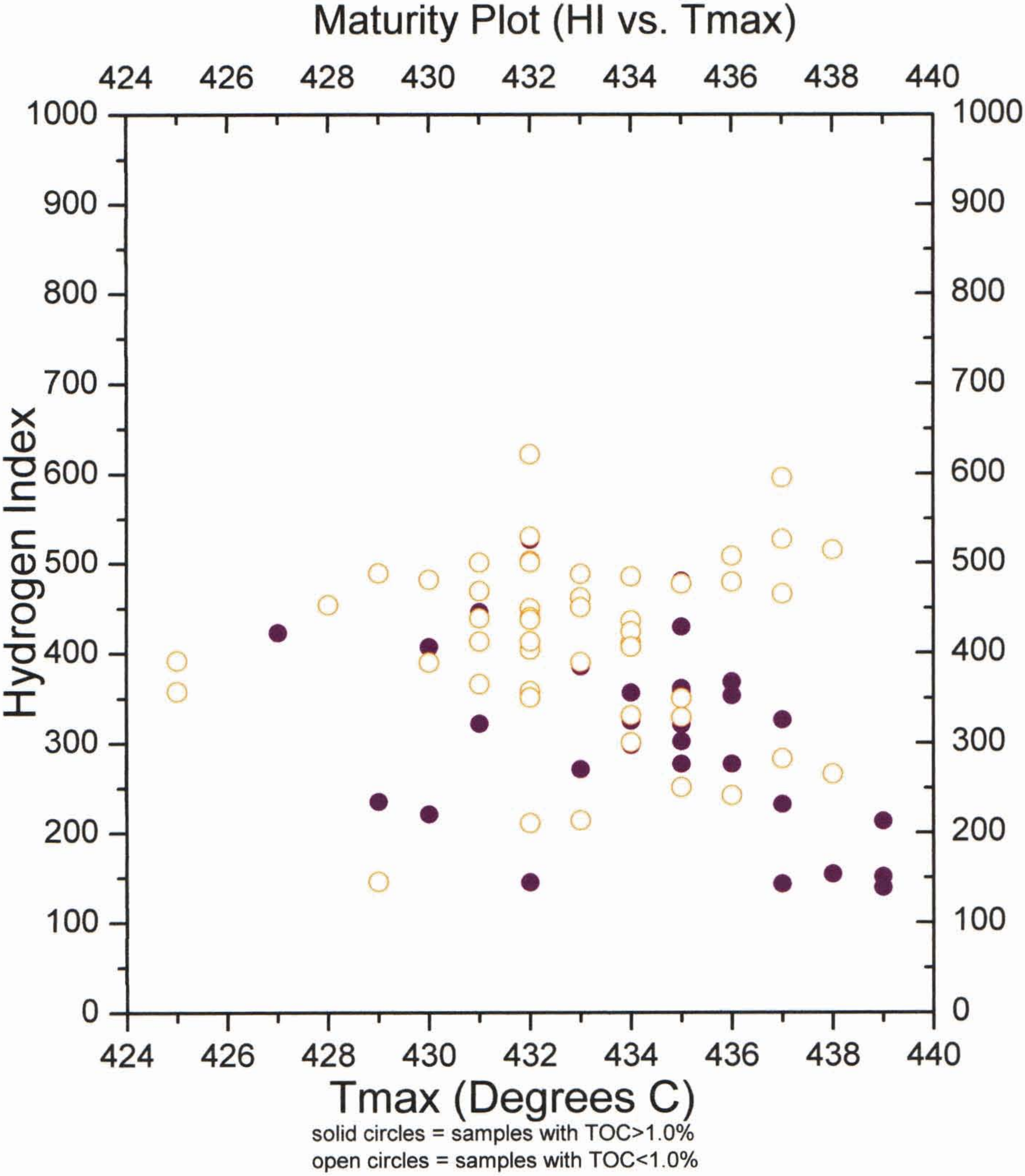

Figure 20. Plot of HI vs. Tmax with differentiation of samples greater than 1.0% TOC and less than 1.0% TOC.

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